Narrowing the Design Space of a Large Membrane Mirror

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Abstract

The mass-optimal design of a large space telescope consists of a thin reflecting membrane over a filled aperture. The application of current engineering knowledge to the realization of a membrane telescope leads to a fairly comprehensive view of what systems and technology will be required. The intent of this paper is to explore the development of this design and roadmap some of the technologies required to achieve this system.

1 Introduction

Because the diffraction-limited angular resolution of a telescope is directly related to the aperture diameter, larger and larger size space telescopes are desirable for both the astronomical and Earth-observation communities. While this desired size is increasing, the size of launch vehicles is remaining the same. This combination of increasing aperture size and limited launch dimensions pushes the designs in the direction of mass-optimal telescope construction. For a reflector telescope this mass-optimal design would consist of a reflective layer just thick enough to reflect the science wavelength. Such a thin mirror will have little bending stiffness and will hence behave as a membrane over large diameters.

The design space of large spaceborne telescopes can be viewed from several perspectives, such as that of optician, systems analyst, or dynamicist, and so a few assumptions are made for this paper. In accordance with the apparent standards of large telescope design, an on-axis, filled-aperture reflector will be considered. The science wavelength will be in the infrared (IR) or visible range; thus the standard wavefront error RMS requirement of $\frac{1}{10}$ the wavelength results in submicron-level RMS position requirements across the mirror. For this paper, all examples are worked for a $20m$ diameter system.

2 Engineering Issues

By making these reasonable assumptions about the optics, we can concentrate on other issues that greatly affect design decisions. Examination of the structures, control, and systems issues related to launching and operating a flexible, high-performance mirror leads to a somewhat constrained design space. The development of this technology can then be mapped out in an effort to identify technology for study.

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2.1 Fundamental Frequency

The attitude control system (ACS) effects rigid body motion of the spacecraft as part of target acquisition and stationkeeping responsibilities. When flexible components are included on a spacecraft, a method to mitigate dynamic structural excitation is to preshape the ACS commands to roll off in magnitude before the first structural frequency. Since the lowest structural frequencies usually form the largest portion of the structural response, decreasing the magnitude of the disturbance before the first structural frequency significantly decreases the dynamic structural response.

The governing equation for a membrane is given in Graff [3] as

$$Q\nabla^2 w(x,y,t) + f_z(x,y,t) = \rho h \ddot{w}(x,y,t) \tag{1}$$

for membrane force $Q(\frac{N}{m})$, transverse displacement w, in-plane coordinates x and y, membrane thickness h, distributed load $f_z(\frac{N}{m^2})$, and material density ρ. The structural frequencies of a membrane, the eigenvalues from this governing equation, are directly related to the in-plane tensile forces in the membrane. Thus a tensile stress state is required in the membrane in order to achieve a fundamental frequency near or above the roll-off frequency of the attitude control system. Looking at the fundamental frequency of a flat circular membrane [12] provides insight into this issue.

$$\omega_1 = \frac{1}{2}\lambda_1\sqrt{\frac{Q}{\rho A h}} \tag{2}$$

where A is the membrane area, $\lambda_1 = 1.357$ is a constant from the exact solution, and ω_1 is the fundamental frequency in Hz. For coated films, the area densities of the different layers sum together.

$$\rho h = (\rho h)_{substrate} + (\rho h)_{coating} \tag{3}$$

For a $20m$ membrane consisting of a $0.5\mu m$ Al coating on $100\mu m$ of nylon film, the relationship betweeen fundamental frequency and tension can be determined from Eqn 2

$$Q = 96.5\omega_1^2 \tag{4}$$

for material properties $\rho_{nylon} = 1400\frac{kg}{m^3}$ and $\rho_{Al} = 2700\frac{kg}{m^3}$. While thinner materials may decrease the coefficient 96.5 as much as an order of magnitude, this squared relationship makes the tension requirement significant for modest desired fundamental frequencies. Note also that the dependence of the fundamental frequency upon the area indicates that the membranes may be diameter-limited unless a new structural control scheme is developed.

2.2 Structures

Deployment The large ratio between deployed mirror diameter and launch vehicle size combined with the accuracy requirements of an IR/optical telescope creates a challenging deployment problem. Decisions about the deployment procedure affect the technology required in other subsystems, and hence deployment is a serious systems concern. For example, the alignment of segments increases the difficulty of the sensing and actuation requirements while possibly decreasing the complexity of the deployment process. The presence of wrinkles and creases degrades the optical performance, and so the stowed radius of curvature will be limited. Decisions about the deployment of membrane mirrors are integral to the development of structural control technology.

Support of the Membrane The structural support of the membrane fulfills different interacting roles. First the rim must be positioned to tolerances similar to the mirror requirements over the entire circumference. Next the rim support must provide enough stiffness to be the reaction structure for the application of membrane tension. Lastly, the rim support connects the membrane to the rest of the telescope structure. Thus the membrane mirror rim support must provide a highly accurate and stable mirror boundary condition while receiving disturbance inputs from other locations in the spacecraft.

2.3 Control

The Control System The goal of the control system will be to autonomously capture the optical figure of the telescope (from the state of maximum error), calibrate the mirror and telescope, and maintain that figure during all image-taking events. The achievement of optical figure can be conceptualized as a series of subsystem figure problems, from (1) the figure of the primary mirror, (2) the figure of any subsequent optics, and (3) the phasing between the primary mirror and subsequent optics. The difficulty of performing these control tasks is defined by how the whole system is built, and so questions of linearity, accuracy, and complexity must be addressed.

The selection of actuators and sensors is not a straightforward task for these large membrane structures. The type and distribution of both the actuators and sensors must be decided in accordance with the chosen structure and deployment system. For instance, the introduction of segments into the design also brings issues of sensing and actuating the segment boundaries. At a fine scale the sensors must be able to observe the minimum number of Zernike modes set by the optical designer. At a larger scale the mirror position must be sensed in order to bring the mirror into figure.

2.4 Distributed Actuation

Distributed actuators on the primary mirror provide a means of adjusting the local mirror shape, a feature that inflation cannot provide by itself. Methods that involve direct contact affect only a small region of the small-bending-stiffness mirror surface, and so very little correction can be performed without a prohibitively large number of actuators. Thus a noncontacting method of distributed actuation is desirable.

Both electromagnetic and thermal fields can be applied to a membrane from a short distance, and so the use of such fields can be exploited through either a normal material response or a so-called "smart material" behavior.

The entire membrane can be controlled nonintrusively (without contact) by application of

1. An electromagnetic field that actuates according to:
    - (a) Electrostatic forces (E-field $\Rightarrow$ force)
    - (b) Piezoelectric effect (E-field $\Leftrightarrow$ strain, with hysteresis)
    - (c) Electrostrictive effect (E-field $\Leftrightarrow$ strain, with hysteresis)
    - (d) Magnetostrictors (B-field $\Leftrightarrow$ strain, with hysteresis)
2. A thermal gradient that actuates according to:
    - (a) Thermal expansion (ΔT $\Rightarrow$ strain)
    - (b) Shape memory response (ΔT $\Rightarrow$ strain, with hysteresis)

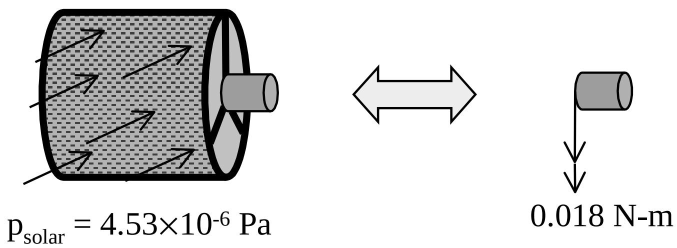

Figure 1: Equivant moment due to solar pressure.

3. A charge field that actuates according to:
   (a) Electrostatic forces (E-field ⇒ force)
   (b) Piezoelectric effect (E-field ⇔ strain, with hysteresis)

Of all of the methods, only the application of electrostatic forces provides a method for distributed actuation, a means to introduce in-plane tension (the reaction to pressure-type loading, and relatively few bandwidth limitations.

2.5 Thermal/ Environment

The space environment introduces disturbances into the space telescope because of the combination of near-vacuum and intense solar radiation. While illuminated surfaces heat and expand on the way to achieving thermal equilibrium with the solar input, shaded surfaces equilibrate with the extremely low temperatures of space. This difference between exposed and shaded surfaces can create thermally-caused distortions. In order to both avoid thermal distortions across the primary mirror and reduce stray light input, a shroud will be expected over a large space telescope. This shroud may also serve other purposes such as a location for solar power cells.

The large, low-mass telescope designs will be susceptible to pressure loading of the primary mirror and thermal shroud. If the mass at one end of the telescope dominates the mass of the spacecraft (a reasonable scenario), the aerodynamic center near the middle of the telescope assembly will be far from the center of mass near the end. Thus any pressure acting upon the telescope will result in a static moment being applied to the spacecraft. Placement in geostationary orbit mitigates the concerns about atmospheric drag, but the pressure from the flux off the sun must be considered. For an approximation, take the solar pressure to be the average solar flux from Larson and Wertz [7] divided by the speed of light, and ($p_{solar} \equiv 4.53 \times 10^{-6} \frac{N}{m^2}$. For a $20m$ f/1 telescope with an approximately $20m \times 20m$ cross-section, the solar pressure produces a maximum static moment of $0.018N \Leftrightarrow m$ on the spacecraft (Fig 1).

2.6 Communication

The communication system may affect the mass distribution of the telescope and hence the structural design. If the spacecraft bus is located at the primary mirror, also a traditional location for the optical bench, the large primary mirror will block the path from the bus to ground. The communications could take place under the following scenarios:

1. The spacecraft bus communicates with on-orbit relay satellite.

2. The spacecraft bus is located at the primary focus, with a clear path to Earth (as in 1996 NASA Inflatable Antenna Experiment [2]).

3. The communications antenna is mounted to the back side of secondary while the bus is behind the primary.
4. A creative solution is found, for example, by exploiting the obscured center region of the primary mirror. or distributing the antenna across an existing membrane or support surface.

The best configuration from a structures viewpoint is for the mass to be concentrated and a light, stiff structure to be attached.

3 Envisioned System

3.1 Working Assumptions

After considering the technical issues presented here, a set of "working assumptions" about large membrane mirror telescopes can be developed.

1. A membrane primary mirror for large apertures is desirable. The membrane represents the smallest amount of mass for a given size reflector.
2. A membrane mirror telescope is viable; no physical barriers have been established for the membrane mirrors.
3. The aperture will be filled yet partially obscured by other optics.
4. No intrusive actuators will act upon the the mirror surface.
5. The fundamental mirror structural frequency must occur after the roll-off of the main disturbance source (the ACS or other).
6. Thermal isolation is required to reduce the effects of thermal expansion. Electrical isolation may also be required if electrostatic forces are to be used.
7. The science light cannot transmit through a lenticular surface. If a large membrane mirror were to be inflated, a transparent film–the lenticular surface– would be inflated opposite the mirror. The science light would travel through this surface a minimum of two times, and maintaining an optical-quality wavefront through these transmissions would be extremely difficult. This assumption rules out simple inflation of the primary.

3.2 The Architecture

These working assumptions, when combined with the engineering issues of section 2, lead to a narrowed design space for large membrane mirror telescopes.

1. The primary mirror membrane can be manipulated at the outer rim and inner rim of the annular structure.
2. An electromagnetic field distributed across the mirror area can provide a noncontact method of capturing and maintaining mirror figure.
3. Developing a tension in the membrane will raise the fundamental so that structural excitation is reduced.

4. Placing a shroud around the entire telescope assembly will provide thermal (and maybe electrical) shielding from the space environment.

5. Determining the mass distribution of the telescope according to the system needs are required for a proper analysis and design of the structural sytems.

The most important unknown in this formulation is the method of deployment. How the deployment is accomplished will greatly affect the requirements of all of the other systems. The actuation, structural support, and sensor designs all strongly depend upon the type of system which results from the deployment decisions.

4 Past Work

The Air Force Research Laboratory in Albuquerque has promising results on the feasibility of a membrane as a primary mirror surface [9, 8]. The configuration there involves a relatively thick film that is figured by a combination of boundary conditions and applied differential pressure. Support and shape adjustment of a large deployed system has been studied experimentally on a $15m$ antenna design at NASA-Langley [1].

The inflated membrane behavior has been studied extensively by L'Garde, the company with the most flight experience in space inflatable structures. L'Garde has shown membrane modelling capability [11] as well as experimental capability with some of the more advanced concepts like rigidization [5]. With the support of NASA-JPL, L'Garde inflated a $14m$ antenna with moderate success in 1996 after release from the space shuttle [2]. The University of Colorado has also produced membrane models that can predict the initial membrane shape given the desired final conditions [4].

Nonintrusive manipulation of membranes has been studied in the form of electrostatically-controlled membrane mirrors. A significant amount of research was performed in this area during the early 1980's, and the work of Mihora and Redmond [10] is an excellent primer for the field. Research on the nonlinear control aspects of electrostatically controlled membrane mirrors is currently being pursued at the University of Michigan [6].

To summarize the state of the art technology,

1. No deployed primary mirrors have been used for optical/IR space telescopes.

2. Many of the technologies have been tested with massive, stiff components. The back planes for electrostatic control have been rigid, and the boundary condition for membrane mirrors is usually an optically-polished surface.

3. The large-aperture spaceflights have been communication antennas. Diameters on the order of $30m$–$40m$ have been flown, but the antenna tolerances are on the order of centimeters.

5 Roadmap of Technology Development

Figure 2 shows one way of viewing the technology development required to proceed from the current state of the art to the goal of a deployed membrane mirror. Consistent with this paper, this roadmap is motivated by the major technology drivers of structures, control, and systems issues. From the current state of the art in rigid-rim membranes figured by gas pressure, technology should be

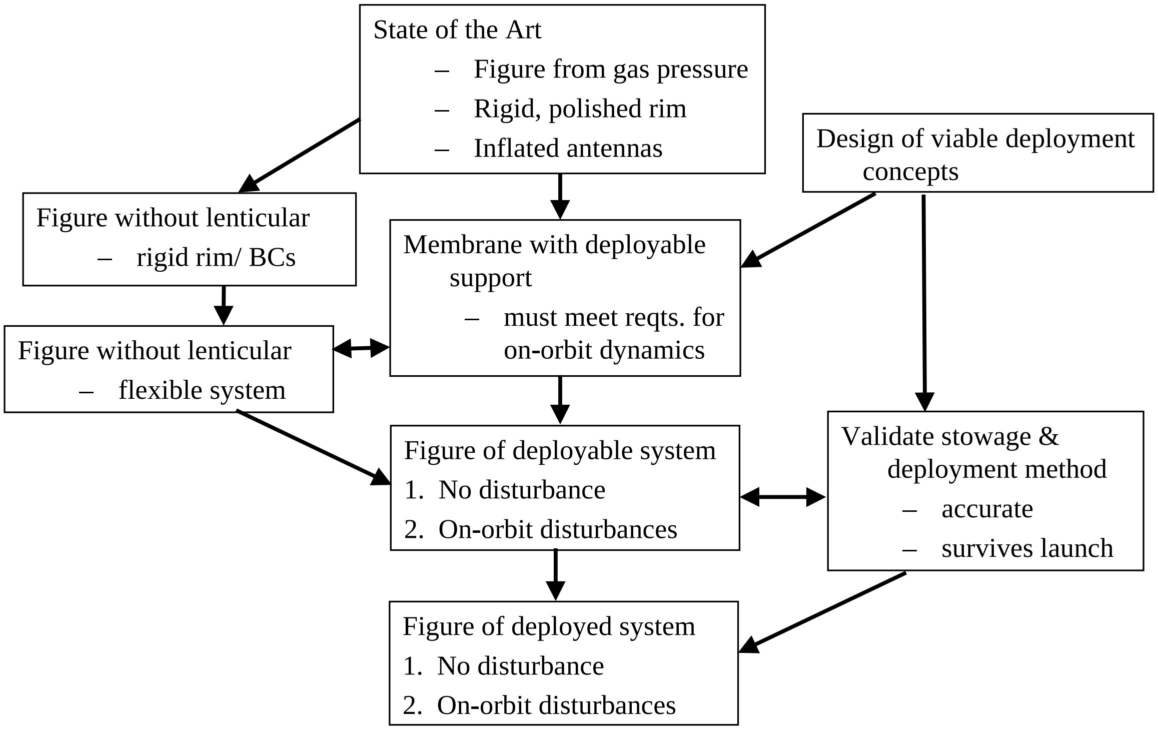

Figure 2: Technology roadmap

developed for flexible-rim sytems without lenticular surfaces. The University of Michigan research, for example, is the furthest down the chart in the “Figure without lenticular: rigid rim” box.

One way to view this development chart is to see the left side as the development of distributed control, the right side as the deployment development, and the middle as the development of flexibility in the system. The goal is to first demonstrate a working *deployable* system – one with enough flexibility to be representative of a deployed system. Then a valid deployment concept can be incorporated in order to demonstrate a working *deployed* system. The double arrows showing the interchange of technology between the deployment concept and the deployable system are extremely important; this connection ensures traceability to a feasible on-orbit design.

6 Conclusions

In this paper we have explored some structures- and control-dominated issues that influence the way in which a large membrane space telescope is designed and researched. The deployment concept is seen to be highly intertwined with the requirements on the other systems; that is, the deployment concept should be condered seriously at the beginning of the research so that the related work is traceable to an on-orbit design.

The annular mirror membrane itself is shown to have position and tension requirements with inputs entering in only three ways: at the outer rim, at the inner rim, and nonintrusively across the back side. The addition of structural flexibility into the systems presents an important next step in creating technology for large spaceborne membrane mirrors.

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